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Quarkonium Physics at a Fixed-Target Experiment using the LHC Beams

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Abstract We outline the many quarkonium-physics opportunities offered by a multi-purpose fixed-target experiment using the p and Pb LHC beams extracted by a bent crystal. This provides an integrated luminosity of 0.5 fb^{-1} per year on a typical 1cm-long target. Such an extraction mode does not alter the performance of the collider experiments at the LHC. With such a high luminosity, one can analyse quarkonium production in great details in pp , pd and pA collisions at $\sqrt{s_{NN}} \simeq 115 \text{ GeV}$ and at $\sqrt{s_{NN}} \simeq 72 \text{ GeV}$ in PbA collisions. In a typical pp (pA) run, the obtained quarkonium yields per unit of rapidity are 2-3 orders of magnitude larger than those expected at RHIC and about respectively 10 (70) times larger than for ALICE. In PbA, they are comparable. By instrumenting the target-rapidity region, the large negative- x_F domain can be accessed for the first time, greatly extending previous measurements by Hera-B and E866. Such analyses should help resolving the quarkonium-production controversies and clear the way for gluon PDF extraction via quarkonium studies. The nuclear target-species versatility provides a unique opportunity to study nuclear matter and the features of the hot and dense matter formed in PbA collisions. A polarised proton target allows the study of transverse-spin asymmetries in J/ψ and Y production, providing access to the gluon and charm Sivers functions.

Keywords Quarkonium Production · Fixed-Target experiment · Large Hadron Collider

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1 Introduction

Fixed-target hadroproduction experiments have played a major role in quarkonium physics, beginning with the co-discovery of the J/ψ [1] at BNL in 1974, the discovery of the Y [2] and the first observation of h_c [3] at Fermilab. Fixed-target experiments have revealed many novel and unexpected features of quark and gluon dynamics, including the anomalous suppression of J/ψ [4] in PbPb collisions at SPS, the strong non-factorising nuclear suppression of J/ψ hadroproduction at high x_F [5] and the large- x_F production of J/ψ pairs [6].

As we have discussed in Ref. [7], the collisions of the LHC proton and heavy-ion beams on fixed targets provide a remarkably large range of physics opportunities thanks to the high luminosity typical of fixed-target experiment and due to its relatively high center-of-mass (CM) energy, 115 GeV per nucleon with the proton beam and 72 GeV per nucleon with the lead beam. This is half way between the CM energies of SPS and RHIC, allowing for detailed studies of bottomonium production and dynamics.

With a nine-month-per-year proton program, one would be able to study the production of quarkonia in pp , pd and pA collisions with a statistical accuracy never reached before, especially in the target-fragmentation region $x_F \rightarrow -1$. One also has the possibility to explore the region $x > 1$ in detail. High-precision quarkonium-production measurements in pp are of highest relevance to help solving the longstanding puzzles in J/ψ and Y production. In particular, it is important to measure observables such as the polarisation parameters of the direct yields; this means that we should be able to subtract precisely yields from excited states such as the P -waves through their decay into J/ψ and Y plus a photon. P -wave studies are also very important *per se*, as well as those of the ground states η_c and η_b . A convincing picture of quarkonium production would only be obtained once a mechanism or a set of mechanisms can be identified as the dominant ones for all quarkonia. Once this is done, most likely also thanks to LHC results, quarkonia should be reconsidered as very competitive probes of gluon –and charm quark– distribution, $g(x)$, as it was done 25 years ago [8, 9] – quarkonium-production yields are proportional to the square of $g(x)$. In this case, a specific emphasis on the study of quarkonia at low P_T and for negative x_F in pp and pd should pose very stringent constraints on $g_p(x)$ at mid and large x but also on $g_n(x)$ which is pretty much unknown.

As aforementioned, fixed-target experiments provided very important information by accessing the large positive x_F limit, where novel QCD effects appear and break factorisation. In comparison, the *large* negative x_F region, which we refer to as the backward limit, has never been explored. HERA-B is thus far the only experiment which could systematically access the region of negative x_F . It could however not go below $x_F \simeq -0.3$ for J/ψ [10] for instance. As we shall elaborate later, the backward limit in pA is interesting in many respects since it is essentially different from the forward limit.

The LHC Pb-one-month program will tell us much on Quark-Gluon Plasma (QGP) which should be created at $\sqrt{s_{NN}} = 72$ GeV in PbA collisions. Yields close to that of LHC at 5.5 TeV and RHIC at 200 GeV are expected. These are two orders of magnitude larger than at RHIC at 62 GeV. The first results from the LHC at 2.76 TeV [11, 12, 13] confirmed that the pattern of quarkonium –anomalous– suppression at high energy is very intricate with subtle y and P_T dependences. Low energy experiments, where recombination process [14] cannot be significant, may then play a key role, especially if the recent ultra-granular calorimetry technology allows one to measure χ_c and even χ_b production and suppression in heavy-ion collisions –thus far two measurements not available in any other experimental configuration. In such a case, the quest of the sequential suppression of quarkonia as a QGP thermometer would be realistic again.

A further advantage of a fixed-target set-up is the possibility of polarising the target. A transverse polarisation would add the possibility of studying spin correlations such as the non-factorising [15, 16, 17, 18] aspects of the Sivers effect which pins down –for gluon sensitive observables– the correlation between the gluon k_T and the nucleon spin. Such measurements could obviously be done with quarkonia at AFTER, following the pioneer studies by PHENIX [19] $p^\uparrow p \rightarrow J/\psi X$.

2 Quarkonium studies with hydrogen target: resolving the production puzzle

2.1 Short historical account of the progress since the mid 90's

Although quarkonia are among the most studied bound-quark systems, one should concede that, for the time being, there is no consensus concerning which mechanisms are effectively at work in their production in high-energy pp collisions, that is at RHIC, at the Tevatron and, recently, at the LHC. For recent reviews, the reader is guided to [20, 21] along with some perspectives for the LHC [22].

Historically, the first puzzle was uncovered by the first measurements of the *direct* production of J/ψ and ψ' at $\sqrt{s} = 1.8$ TeV by the CDF Collaboration [23, 24] whose rates at mid and large P_T were found to be much larger than the LO prediction of the QCD-based approach of the Colour-Singlet Model (CSM) [25]. The first NLO evaluations only appeared for the J/ψ and Y for the yields in 2007 [26], for the polarisation in 2008 [27] and for the χ_c yields [28] in 2010.

In the meantime, other approaches were introduced (*e.g.* the Colour-Octet Mechanism (COM) from NRQCD [29]) or revived (*e.g.* the Colour-Evaporation Model (CEM) [30]). Unfortunately, these mechanisms –despite their lower predictive power compared to the CSM– are also not able to reproduce in a consistent way experimental studies of both cross-section and polarisation measurements for charmonia at the Tevatron [31, 32] along with those measured at RHIC [33, 34, 35] and at the LHC [36, 37, 38, 39, 40]. As an example, the seemingly solid COM prediction of a transverse polarisation of ψ' produced at high P_T is clearly challenged by the experimental measurements [31]. Recent global fit analyses of J/ψ CO Matrix Elements (MEs) [41, 42] –consistent with universality– strongly differ in their conclusion when confronted with polarisation data due to a large effect of the choice of the fit sample. This is actually worrisome. Such a difficulty of NRQCD can be naturally explained if the charmonium system is too light for the relativistic effects to be neglected¹ and for the NRQCD [29] quark-velocity expansion (v) to be applied for the rather “light” $c\bar{c}$ system. This may very well be so in view of the agreement between theory and the available experimental data on production in pp of the significantly heavier Y . The CSM NLO predictions including real-emission NNLO contributions at α_S^5 –the NNLO*– [44] show near agreement [45, 46] at mid P_T with the J/ψ and ψ' data coming from the Tevatron [23, 24, 47] and the LHC [36, 37, 38, 39]. However, at large P_T , a gap persists between charmonium data and the CSM predictions.

As regards the total P_T -integrated ψ yield, we should note that it is also very well described by the sole CS contributions [48, 49] from RHIC energy all the way to that of the LHC. This is supported by the results of recent works [50] focusing on production at e^+e^- colliders which have posed stringent constraints on the size of $C = +1$ CO contributions which can be involved in hadroproduction at low P_T ; this is reminiscent of the broad fixed-target measurement survey of total cross sections [51] which challenged the universality of the CO MEs. Finally, let us note that the early claim –based on a LO analysis [52]– of evidence for COM in $\gamma\gamma J/\psi$ production has become a difficulty of the COM itself at NLO [41].

In the bottomonium sector, relativistic corrections should be smaller and the leading Fock state, that is the CS 3S_1 state, should be dominant. This explains why the inclusion of this sole CS channel contribution [45] is sufficient to convincingly reproduce the total yield [48, 49] – as for charmonia– *as well as* the cross section differential in P_T [45] – when P_T^{-4} contributions are included– from RHIC [53], the Tevatron [54, 55] and the LHC [56, 57, 58].

Finally, it is interesting to mention here the first spin results on quarkonium obtained at RHIC. That is the measurement by PHENIX [19] of an increasing asymmetry, A_N , in $pp^\uparrow \rightarrow J/\psi X$ for increasing x_F , in favour –following the argument of [59]– of the CS dominance of low P_T . We will come back to this in the section 8.1.

2.2 AFTER-wish-list to solve the puzzles

Quarkonium measurements in unpolarised pp collisions can be divided in 3 categories: (i) yields (differential in P_T or y), (ii) polarisation or spin alignment and (iii) associated production. We postpone the discussion of the last topic to section 8.2. For each, we briefly discuss available and missing data. At the end, we list the needs for forthcoming analyses, most of which would be carried at AFTER.

2.2.1 Yields and differential cross-section measurements in high-energy pp collisions²

In most cases, theoretical predictions are most precise when one refers to *direct* yields, those which do not include any feed-down from higher excited states or B decays –in the case of charmonia. It is therefore very important to have as many such measurements as possible. Despite this, prompt measurements may still be useful provided that the feed-down is known in a similar phase-space region.

As for now, direct yields are known –by order of reliability– for $Y(3S)$, ψ' , J/ψ , $Y(2S)$ and $Y(1S)$. As regards J/ψ , the χ_c feed-down measurements have been carried out only twice at colliders for mid y by CDF

¹ Along these lines, see the very interesting recent study [43] of the v^2 correction for CO channels which seem to be significant.

² We restrict ourselves to the discussions of the AFTER, RHIC, Tevatron and LHC energy domain, that is from 100 GeV upwards.

during Run-1 [24] and by PHENIX [60]. The CDF measurements are differential in P_T –with only 4 bins, though–, but do not extend to low P_T . These analyses have never been cross checked. Only a single χ_b feed-down measurement exist, and is not differential in P_T . One cannot tell anything on a possible variation of the χ_b feed-down fraction with P_T .

The χ_c and χ_b feed-down fraction extractions are therefore one of the top priorities in quarkonium-production studies. They would provide stringent constraints on the theoretical models. *Per se*, P -wave yields are also very important since they can now also be confronted with accurate theoretical predictions, for instance at NLO [28] or in k_T factorisation approaches [61, 62] (see also section 3.3 of [20]). Such measurements are also of paramount importance at low P_T (below 3 GeV) to test predictions of the total direct yields.

One should also note that extending measurements of P_T spectrum up to very high values –100 GeV or more– is not necessarily optimal, since the dominant production mechanisms in this region are not necessarily those in the mid- P_T region and because of the presence of large logarithms of P_T/m_Q in the theory at fixed order in α_s .

2.2.2 Polarisation

There have been much fewer studies of quarkonium polarisation. For instance, not a single measurement of the polarisation of the *direct* J/ψ , $Y(1S)$ and $Y(2S)$ exists or is even under study. Only such data exist for ψ' [31], although with a limited precision, or may be delivered for $Y(3S)$. Beside this, it has been recently emphasised [63, 64] that the sole measurement of the polar– θ – anisotropy, the so-called α or λ_θ parameter, is not sufficient to extract all the information about the quarkonium polarisation and it can be strongly biased by the acceptance of the experimental set-up. Ideally measurements should either be done using multiple frames (by changing the spin-quantisation axis) or by studying both the θ and ϕ angular dependence (2D analysis) of the quarkonium decay products.

The needs are simple to list –but likely very demanding for LHC experiments for instance. One clearly needs a cross check of the prompt –that is direct– ψ' polarisation in 2 frames or in 2D, preferably differential in P_T (up to 20 or 30 GeV where theoretical predictions do differ) and differential in y . The same should also be done for $Y(3S)$. This would be a very good starting point to discriminate models.

However, nothing guarantees that the production mechanisms of these excited states are *de facto* the same as of J/ψ and $Y(1S)$. Similar analyses would require subtracting the polarisation induced by the P -wave feed-down, which is probably a highly complicated task. Given the theoretical situation, this is however what seems to be required to pin down the specific mechanisms at work in J/ψ and $Y(1S)$ hadroproduction. If this appears to be out of experimental reach, investigating associated-production channels will be advantageous. These are discussed in section 8.2.

2.2.3 Wish-list summary

According the above discussion, we can summarise the present needs as follows:

1. cross-check studies of the *direct* J/ψ yield (χ_c only measured once by in pp by CDF and once by PHENIX);
2. cross-check studies of the *direct* $Y(1S, 2S)$ yields (χ_b only measured in pp by CDF (for a single P_T bin));
3. polarisation studies of the *direct* yields at least in 2 frames or with a 2D analysis for J/ψ , ψ' and $Y(3S)$ (only known for ψ' in 1 frame);

Given the many advantages offered by AFTER, the very large yields –3 orders of magnitude above those at RHIC (see Table. 1)–, a potentially very good acceptance at low P_T thanks to the boost, the likely excellent muon energy resolution, the availability of novel particle-flow techniques for photon detection in high-multiplicity environment, one is hopeful that most of –if not all– these measurements could be carried out thanks to AFTER. Obviously, in 10 years from now, LHC results would be also strongly complementing this existing picture with very high energy data.

³ The luminosity for RHIC are taken from the PHENIX decadal plan [65].

| Target | $\int dt \mathcal{L}$ | $\mathcal{B}_{\ell\ell} \frac{dN_{J/\psi}}{dy} \Big _{y=0}$ | $\mathcal{B}_{\ell\ell} \frac{dN_Y}{dy} \Big _{y=0}$ |
|-------------------------------|-----------------------|---|--|
| 100 cm solid H | 26 | $5.2 \cdot 10^8$ | $1.0 \cdot 10^6$ |
| 100 cm liquid H | 20 | $4.0 \cdot 10^8$ | $8.0 \cdot 10^5$ |
| 100 cm liquid D | 24 | $9.6 \cdot 10^8$ | $1.9 \cdot 10^6$ |
| 1 cm Be | 0.62 | $1.1 \cdot 10^8$ | $2.2 \cdot 10^5$ |
| 1 cm Cu | 0.42 | $5.3 \cdot 10^8$ | $1.1 \cdot 10^6$ |
| 1 cm W | 0.31 | $1.1 \cdot 10^9$ | $2.3 \cdot 10^6$ |
| 1 cm Pb | 0.16 | $6.7 \cdot 10^8$ | $1.3 \cdot 10^6$ |
| pp low P_T LHC (14 TeV) { | 0.05 | $3.6 \cdot 10^7$ | $1.8 \cdot 10^5$ |
| | 2 | $1.4 \cdot 10^9$ | $7.2 \cdot 10^6$ |
| pPb LHC (8.8 TeV) | 10^{-4} | $1.0 \cdot 10^7$ | $7.5 \cdot 10^4$ |
| pp RHIC (200 GeV) | $1.2 \cdot 10^{-2}$ | $4.8 \cdot 10^5$ | $1.2 \cdot 10^3$ |
| dAu RHIC (200 GeV) | $1.5 \cdot 10^{-4}$ | $2.4 \cdot 10^6$ | $5.9 \cdot 10^3$ |
| dAu RHIC (62 GeV) | $3.8 \cdot 10^{-6}$ | $1.2 \cdot 10^4$ | $1.8 \cdot 10^1$ |

Table 1: Nominal yields for J/ψ and Y inclusive production for the quarkonium rapidity $y \in [-0.5, 0.5]$ expected per LHC year with AFTER with a 7 TeV proton beams on various targets compared to those reachable – also for $y \in [-0.5, 0.5]$ – (i) at the LHC in pp at 14 TeV with the luminosity to be delivered for LHCb and ALICE (which have a low P_T J/ψ coverage), (ii) in a typical LHC pPb run at 8.8 TeV, (iii) at RHIC³ in pp and (iv) in dAu collisions at 200 GeV as well as in dAu collisions at 62 GeV. The integrated luminosity is in unit of fb^{-1} per year, the yields are per LHC/RHIC year.

3 Mid and large- x gluon-PDF extraction from quarkonium yields

One of the limitations of Deep-Inelastic-Scattering (DIS) experiments is that they only directly probe the target quark content. It is difficult to directly probe the gluons, although they carry a large fraction –40% at $Q^2 \simeq 10 \text{ GeV}^2$ – of the proton momentum. Indirect information –mostly at low x – can be obtained from the scaling violation of the quark PDFs. In large- x DIS and DY, PDF extraction is not an easy task due to the presence of higher-twist corrections, such as mass effects [66] and direct processes [67]. In this region, sum rules are also practically useless since the PDFs are strongly suppressed for $x \rightarrow 1$. As a consequence, the gluon distribution is very badly known for $x > 0.2$ at any scale, see for instance Fig 1. of [7].

In this context, the information offered by quarkonium production in the target region at AFTER should be invaluable. In the conventional approach, quarkonia are produced at high energy by gluon fusion at scales of the order of their mass, thence large enough to use perturbative QCD (pQCD). As discussed above, a number of puzzles are complicating the picture. The situation has changed since the pioneering analyses of gluon PDF extraction with quarkonium data [8, 9] and, nowadays, few people still consider quarkonia as reliable probes of gluon distribution. High- P_T jet or even prompt photon studies are preferred. We are however very confident that these puzzles would be solved by the systematic high-precision studies mentioned above in addition with the forthcoming LHC results at high energies and most likely as well for higher P_T . Let us in addition mention the possibility of a contribution at large x by IC via $gc \rightarrow J/\psi cX$ [48] or via diffractive reaction [68]. These are discussed in section 6. Like for other hadronic reactions where different PDFs are involved, extraction of one specific PDF, once the other contributions are known, is possible; this thus calls for the extraction of $c(x)$ and to a lesser extent to $b(x)$.

That being said, the use of $C = +1$ quarkonia, in particular the $\eta_{c,b}$ and $\chi_{c,b}({}^3P_2)$, should in any case be more reliable than of J/ψ . $\eta_{c,b}$ and $\chi_{c,b}({}^3P_2)$ are produced at LO without a final-state gluon [20, 21, 69], hence (i) with very competitive rates and (ii) via a Drell-Yan like kinematics for which the gluon momentum fractions are simply related to the quarkonium rapidity. Last but not least, large QCD corrections to the P_T spectrum predictions, as seen for ψ and Y [26, 70, 27, 44], are not expected since the leading- P_T scaling is already reached at NLO.

A modern ultra-granular electromagnetic calorimeter [71] should allow one to study both $\chi_{c,b}({}^3P_2)$ through $\ell^+ \ell^- \gamma$ decays and η_c in the $\gamma\gamma$ channels down small P_T and to large negative x_F . With a good Particle IDentification (PID), the study of the $p\bar{p}$ decay channel (see e.g. [72]) is reachable, opening the door to a systematic study of all the hidden charm resonances. Doing so, it is reasonable to consider that, with charmonia, $g(x)$ could be measured accurately for $Q^2 \simeq 10 \text{ GeV}^2$ from x as low as 10^{-3} , and with bottomonia,

for $Q^2 \simeq 100 \text{ GeV}^2$ from $x = 3 \times 10^{-2}$ up to $x \simeq 1$ in the range $y_{onium} \in [-4.8, 1]$. The case for bottomonium is certainly stronger since (i) its production certainly lies in the perturbative domain of QCD for any P_T , (ii) higher-twist contributions and relativistic corrections should also be small, (iii) CO contributions can certainly be neglected, and (iv) the impact of IB should be ten times smaller than that of IC (see section 6).

4 Quarkonium production in proton-deuteron collisions: gluons in the neutron

The most competitive way to study the partonic structure of the neutron is to use combined measurements with hydrogen and deuterium targets. Studies of the gluon distribution in the neutron, $g_n(x)$, are singularly more complicated than those of quarks based on DIS experiments (see [73] for a recent account of existing results) and DY (see *e.g.* [74]). An isospin asymmetry of the sea quarks has for instance been uncovered [74].

As regards the gluon in the neutron, quarkonium hadroproduction seems to be an ideal probe. Muon-production J/ψ studies on proton and deuterium targets by the NMC collaboration [75] showed that –within their 15% uncertainty– $g_n(x)$ was similar to $g_p(x)$. The E866 Υ analysis [76] in pp and pd confirmed that $g_n(x, Q^2 \simeq 100 \text{ GeV}^2) \simeq g_p(x, Q^2 \simeq 100 \text{ GeV}^2)$ for $0.1 \leq x \leq 0.23$. Unfortunately, this measurement could not be done simultaneously for J/ψ which would have probed $g_n(x)$ at lower Q^2 and lower x .

Using a 1m-long deuterium target, one would obtain (see Table. 1) $10^9 J/\psi$ and $10^6 \Upsilon$ decaying in muon pairs in one unit of y in proton-deuteron collisions. Such high-precision measurements may allow for the discovery of a difference between $g_n(x)$ and $g_p(x)$. In any case, such an analysis would allow for the extraction of $g_n(x)$ in a significantly wider x range and at lower Q^2 with J/ψ . It is important to keep in mind that one does not anticipate other facilities where pd collisions could be studied in the next decade – at least at high enough luminosities and energies where such measurements could be carried out.

5 Quarkonium production in pA collisions: taming the nuclear-matter effects

The study of hard hadronic processes in pA collisions gives the opportunity to study a large number of very interesting QCD effects, among others

- the modification of the partonic densities inside bound nucleons;
- the propagation of the hadrons in the nuclear matter during their formation;
- the energy loss of partons which is induced by the nuclear matter, be it absolute or fractional;
- the colour filtering of IC in the nuclear matter;

A high luminosity fixed-target experiment with versatile target choice is the best set-up to explore this physics, which is of significant importance for interpreting the physics of hard scatterings in AA collisions discussed in section 7. This physics is genuinely at the small-distance interface between particle and nuclear physics, it deserves thus much efforts which could be very rewarding in terms of discovery of novel QCD aspects.

It is clear that AFTER is the ideal experiment to illuminate this physics in the sub-TeV domain, taking into account the strength and the weakness of SPS, Fermilab and RHIC experiments. For instance, the major disadvantage of studying (proton-)ion collisions with collider experiments is the intrinsic difficulty to change the beam species. During the past ten years, RHIC studied four kinds of collisions: pp , dAu (equivalent to pAu), $CuCu$ and $AuAu$. The luminosities are also severely limited. No ψ' yield has been measured so far in dAu collisions, while the fixed-target experiment E866 with a versatile choice of targets had enough luminosity to find a difference of the absorption between J/ψ and ψ' at low x_F [77]. However, E866 could not take data simultaneously for charmonium and bottomonium, neither could it look at P wave as did Hera-B. On the other hand, SPS experiments were limited in their rapidity coverage, whereas PHENIX at RHIC can give information over more than 4 units of rapidity. The limitation in energy of SPS also severely limited Υ studies.

To avoid the limitations of past experiments, it appears that the capabilities of a new experiment should at least be:

- Collection of large statistical samples;
- Wide coverage of rapidity and x_F ;
- Wide coverage of A ;
- Simultaneous measurements of most of the quarkonium and open heavy-flavour states.

This is precisely what AFTER can offer above 100 GeV with a multi purpose detector and a large coverage from $y_{cms} \simeq 0$ down to the target rapidity⁴. In practice, in the far – and less far– negative x_F region, we would like to master the effect from the gluon nPDF and from the survival probability of the quarkonium along its way out of the nucleus. These effects should significantly affect quarkonium production, implying in return that they can be analysed thanks to quarkonium.

The plan for high-precision pA quarkonium-production studies essentially bears on the very large yields detailed in Table. 1 at AFTER in pPb collisions for instance, $10^9 J/\psi$ and $10^6 Y$ per year and per unit of rapidity. The target versatility would of course be a strong asset to investigate the dependence on the impact-parameter, b , of nuclear-matter effects, in particular that of the nPDFs [79]. The precision and the interpretation of the RHIC studies –using the sole dAu system– is indeed limited by the understanding and the measurements of the so-called centrality classes. A further key requirement here is to study multiple states to get a handle on factorisation breaking effects in this particular phase-space region.

Let us also note that low- x gluon determination is one of the main aims of Electron-Ion Collider projects (eRHIC, ELIC, LHeC), principally by very precise studies of DIS on proton and nucleus targets as well as of photo- and electro-production of J/ψ . Both EIC and AFTER projects are essentially complementary. However, it is worth noting that gluon-nPDF extraction via quarkonium studies in ep or eA collisions will also require progress in understanding quarkonium hadroproduction. It is reasonable to say that a reliable extraction of $g(x)$ from J/ψ cross sections in ep and eN collisions can only be achieved once the hadroproduction puzzles are behind us.

5.1 Quarkonium production as probe of gluon nPDFs: shadowing, antishadowing and EMC effect

Nuclear PDFs (nPDFs) contain a wealth of information about the dynamics of parton in nuclei. For x larger than unity, they even contain information about the correlations between the nucleons within the nuclei; these are pretty unknown at the GeV scale. Fermi motion is known to alter PDFs at very large x (< 1). Then, a depletion of the PDFs is observed, for $0.3 \leq x \leq 0.7$. It is known since 1983, as the EMC effect, but there is no consensus on its physical origin. At lower x , one observes an excess of partons compared to free nucleons at mid x – the antishadowing. This observation was made in electron-nucleus deep-inelastic reactions, but appears to be absent in the case of Drell-Yan processes in pA and neutrino charged-current reactions [80]. It could be that antishadowing is quark or anti-quark specific because of the flavour dependence of Regge exchange in the diffractive physics underlying Glauber scattering [81, 82] or because it is a higher twist effect. At small x , below say 0.05, a further depletion of nPDFs –the nuclear shadowing [83, 84]– is observed.

Whereas these effects can be studied for quark distributions, there are usually very difficult to probe in the gluon sector. Measurement of low- x gluon shadowing is for instance one of the EIC flagships. At mid- and large- x , it is important to note that gluon-nPDF fits are plagued by large –and sometimes fit-dependent– uncertainties. The amount of the EMC suppression is actually pretty much unknown [85], except for a loose constraint set by momentum conservation. Quarkonia can be key players here. RHIC experiments were the first to extend quarkonium studies in $p(d)Au$ collisions above the 100 GeV limit hinting at gluons shadowing in the Au nucleus [86]. RHIC Y -production data also hint [87] at a gluon EMC effect stronger than for quarks, but higher precision data are needed. It will be difficult for PHENIX and STAR to provide definitive data.

In this context, the large charmonium and bottomonium yield we expect at $\sqrt{s_{NN}} = 115$ GeV, $10^9 J/\psi$ and $10^6 Y$ per year and per unit of rapidity (see Table. 1), should allow for high-precision pA -production studies and in turn give us confidence in gluon-nPDF extraction with quarkonia. A good enough resolution would allow the measurement of ratios of yields such as $N_{J/\psi}/N_{\psi'}$. We would have access to open charm and beauty with vertexing. Other ratios such as $N_{J/\psi}/N_D$ and N_Y/N_B –where the nPDF effect may cancel– could then be extracted. Good photon calorimetry would make a systematic study of χ_c and χ_b possible, extending the measurements of HERA-B [88]. AFTER could provide the first study of η_c inclusive production in pA collisions. A combined analysis of these observables would certainly put stringent constraints on the gluon distribution in nuclei at mid and large x , given that they would also help understand other effects at work on which we elaborate now.

⁴ An idea similar to AFTER has been proposed in [78] using a ribbon-like lead target at the interaction point of the ALICE detector. This also offers rates higher than at RHIC but does not have the versatility of an extracted beam line. In particular, it does not allow for pp and pd measurement with long hydrogen and deuterium targets as discussed above. Neither does it allow for polarised-target analyses.

5.2 Additional physics in quarkonium production in pA

In the negative x_F region, the mesons are also fully formed when escaping the nucleus with a survival probability which is minimal and related to their physical size. In more forward configurations, where the $Q\bar{Q}$ is boosted in the nucleus rest frame, the survival probability is not necessarily related to their size; one thus often parametrises it in terms of an effective cross section. This picture could be checked in detail with a careful study of ratios of yields of different quarkonia (see *e.g.* [89]). A scan in x_F , thus in $\sqrt{s_{\psi N}}$, would help us understanding the physics underlying this effective break-up cross section, which may reveal higher twist effects [90]. *A priori*, this region is not affected by fractional energy loss [91], neither by colour filtering of IC [5], relevant at large x_1 , not at large x_2 . In the negative x_F region, IC may be a natural source of charmonium production but it would not show the $A^{2/3}$ suppression discussed in section 6.

All of these aspects can also be investigated with DY, prompt photon, photon-jet correlation and heavy-flavour measurements at AFTER. This would cross-check –or feed information in– the interpretation done with quarkonia. We emphasise once again that HERA-B is so far the only experiment which could easily access the region of negative x_F , down to -0.3 for J/ψ [10]. No other facility could ever go below that.

6 Heavy-quark (n)PDFs and quarkonia

From the non-Abelian QCD couplings of the gluons [92, 93], one expects the probability of the intrinsic Fock state in a proton $|uudQ\bar{Q}\rangle$ to fall as $1/M_{Q\bar{Q}}^2$. The relevant matrix element is the cube of the QCD field strength $G_{\mu\nu}^3$, in contrast to QED where the relevant operator is $F_{\mu\nu}^4$; the probability of intrinsic heavy leptons in an atomic state is suppressed as $1/m_l^4$. It can be shown that the heavy-quark pair $Q\bar{Q}$ in the intrinsic Fock state is then primarily a colour-octet. The ratio of IC to IB also scales as $m_c^2/m_b^2 \simeq 1/10$. Many aspects of this physics can be studied at AFTER with quarkonia both in pp and pA collisions.

6.1 Intrinsic charm and beauty in the proton

Initial parametrisations of the charm and bottom quark PDFs used in global fits of the proton structure functions only have support at low x since one usually assumes that they only arise from gluon splitting $g \rightarrow Q\bar{Q}$ from Q^2 above $4m_Q^2$ and that the IC or IB component is negligible. Inaccurate predictions can result from this assumption, especially in large x_F or x_T heavy-hadron production. In agreement with the EMC measurements [94], IC predicts that the charm structure function has support at large x in excess of DGLAP extrapolations [95]. It is surprising that the original 1983 EMC experiment which first observed a large signal for charm at large x in $\gamma^*p \rightarrow cX$ has never been repeated. Lai, Tung, and Pumplin [96] emphasised that $c(x)$ may have been underestimated in usual global fit, but dedicated measurements are still awaited for.

Careful analyses of the rapidity distribution of open- or hidden-charm hadrons in a fixed-target set-up at $\sqrt{s} = 115$ GeV are therefore very important –especially at backward rapidities– to learn more on these aspects of QCD. In particular, it has been shown [48] that, at $\sqrt{s} = 200$ GeV, a significant fraction of the J/ψ yield is expected to be produced in association with a charm quark. It was also emphasised that the measurement of the rapidity dependence of such a yield would provide a complementary handle on $c(x)$. Such a measurement would efficiently be done by triggering on J/ψ events then by looking for D into its $K\pi$ decay for instance. At large $|x_F|$, diffractive J/ψ production [68] should arise from IC coalescence. Quantitative predictions of the cross section are however lacking and much can still be learnt. An excess of double J/ψ events may also sign the presence of IC. We believe that a set of precise measurements as the one mentioned above would certainly help in probing IC and measuring its size.

6.2 Intrinsic charm and beauty in the nucleus

AFTER is unique for its access to the negative x_F region, where IC and IB component, not in the projectile, but in the target can have an important effect. As aforementioned, the IC Fock state has a dominant colour-octet structure: $|(uud)_{8C}(c\bar{c})_{8C}\rangle$. In pA collisions for $x_F \rightarrow 1$, the colour octet $c\bar{c}$ comes from the projectile and bleaches into a colour singlet by gluon exchange on the front surface of a nuclear target. It then coalesces to a J/ψ which interacts weakly through the nuclear volume [97]. An $A^{2/3}$ dependence of the rate is expected,

which corresponds to the front-surface area. This combines with the usual pQCD A^1 contribution at small x . This combination is actually consistent with charmonium production observed by the CERN-NA3 [98] and the Fermilab E866 collaborations [77]. Because of these two components, the cross section violates perturbative QCD factorisation for hard inclusive reactions [5]. Other factorisation-breaking effects exist such as Sudakov suppression induced by the reduced phase space for gluon radiation at large x_F [99], fractional energy loss [91], etc. As we discussed in section 5, they all deserve careful analyses.

For negative x_F , the IC emerges from the nucleus and can be affected by nuclear modifications such as anti-shadowing, EMC or Fermi motion. One does not expect colour filtering anymore. AFTER provides a unique opportunity to check this prediction. It has also to be noted that in Pb p collisions at 72 GeV, large negative x_F charmonium production would become again sensitive to colour filtering of IC.

7 Quark-gluon plasma and the quarkonium sequential suppression

Charmonium suppression in relativistic heavy-ion collisions has been first proposed by Matsui and Satz in 1986 [100] as a probe of the formation of a Quark Gluon Plasma (QGP). Since then, many experiments have provided important results on J/ψ production in AA collisions for instance at the CERN-SPS at $\sqrt{s_{NN}}=17$ GeV [101, 102, 4] and at BNL-RHIC at $\sqrt{s_{NN}}=200$ GeV [103, 104, 105]. Results starts now to flow in from the CERN-LHC at $\sqrt{s_{NN}}=2.76$ TeV [11, 12, 13]. These results tend to indicate that the J/ψ -production cross section is indeed modified by the Hot and Dense Matter (HDM) produced at SPS and RHIC, as it was predicted almost 25 years ago. However, a definite and precise description of the HDM effects on J/ψ production is not still at reach.

Among the arguments that can be raised to explain the situation, the lack of knowledge of the nuclear-matter effects is the most relevant one; we discussed it in section 5. One can also argue on the fact that, so far, the main experimental results concern J/ψ production only. Even though ψ' production has been studied in AA at SPS, the statistics available are poor; these are (almost) absent at RHIC. This precludes any sensible interpretation. Other quarkonium measurements such as those of χ_c are so difficult to perform that the available data are useless for our purpose. Such a measurement is however of fundamental interest since around 30% of the produced J/ψ come from the χ_c decay. χ_c and ψ' may melt at a lower QGP temperature than the J/ψ , hence a sequential melting pattern. Finally, the statistics of Y measured at SPS is too low to draw any firm conclusion and, at RHIC, the situation is roughly the same.

The LHC experiments will provide detailed results on AA collisions at an energy $\sqrt{s_{NN}}=2.76$ and 5.5 TeV— never reached before and will offer the possibility to study both charmonium (J/ψ and ψ') and bottomonium ($Y(nS)$) states, shedding light on quarkonium behaviour in such a new HDM regime where most of them are expected to be melted. The process of $c\bar{c}$ recombination [14] might come into play at such high energies. The first results on J/ψ at 2.76 TeV [11, 12, 13] show an unexpected pattern, difficult to explain. In addition, CMS [106] has observed a suppression of excited $Y(2S)$ and $Y(3S)$ states relative to $Y(1S)$ in these PbPb collisions. Further data will complete this list, whose interpretation will remain complicated by the lack baseline of p Pb collisions at the same energy and in the same CM rapidity coverage, even though p Pb runs are planned.

Low energy experiments, where recombination processes [14] cannot be significant, should be very complementary to the forthcoming LHC results. Provided that excited states and different nucleus-nucleus AB systems can also be studied, it is reasonable to argue that the sequential suppression pattern of quarkonium could be observed and used as a thermometer of the QGP in central AA collisions. It is also important to have a good control of nuclear-matter effects which, as discussed above, would then be studied at 115 GeV in pA collisions and which can also be studied at 72 GeV in Pb p collisions with an hydrogen target.

Table. 2 displays the expected J/ψ and Y yields with the 2.76 TeV Pb beam on several targets. They are compared to those expected per year at RHIC in dAu and $AuAu$ (at $\sqrt{s_{NN}} = 62$ and 200 GeV), at the LHC in Pb p (at $\sqrt{s_{NN}} = 8.8$ TeV) and in PbPb (at $\sqrt{s_{NN}} = 5.5$ TeV) at their nominal luminosity. The yields in PbPb (at $\sqrt{s_{NN}} = 72$ GeV) are similar to (100 times larger than) those expected in a year at RHIC for $AuAu$ at $\sqrt{s_{NN}} = 200$ GeV (62 GeV) and also similar to that to be obtained during one LHC PbPb run. This is remarkable considering the lower cross section at AFTER because of the lower energies. We note that the same ratios also apply for the other quarkonium states. The baseline for such collisions could be measured with the Pb beam with a 100cm thick H target, with very competitive rates.

Thanks to recent developments in ultra-granular calorimetry techniques, one expects be able to study other charmonium states such as χ_c in its $J/\psi + \gamma$ decay channel. This would help towards the understanding

| Target | $\int dt \mathcal{L}$ | $\mathcal{B}_{\ell\ell} \left. \frac{dN_{J/\psi}}{dy} \right _{y=0}$ | $\mathcal{B}_{\ell\ell} \left. \frac{dN_Y}{dy} \right _{y=0}$ |
|-----------------------|-----------------------|--|---|
| 100 cm solid H | 1100 | $4.3 \cdot 10^6$ | $8.9 \cdot 10^3$ |
| 100 cm liquid H | 830 | $3.4 \cdot 10^6$ | $6.9 \cdot 10^3$ |
| 100 cm liquid D | 1000 | $8.0 \cdot 10^6$ | $1.6 \cdot 10^4$ |
| 1 cm Be | 25 | $9.1 \cdot 10^5$ | $1.9 \cdot 10^3$ |
| 1 cm Cu | 17 | $4.3 \cdot 10^6$ | $0.9 \cdot 10^3$ |
| 1 cm W | 13 | $9.7 \cdot 10^6$ | $1.9 \cdot 10^4$ |
| 1 cm Pb | 7 | $5.7 \cdot 10^6$ | $1.1 \cdot 10^4$ |
| d Au RHIC (200 GeV) | 150 | $2.4 \cdot 10^6$ | $5.9 \cdot 10^3$ |
| d Au RHIC (62 GeV) | 3.8 | $1.2 \cdot 10^4$ | $1.8 \cdot 10^1$ |
| AuAu RHIC (200 GeV) | 2.8 | $4.4 \cdot 10^6$ | $1.1 \cdot 10^4$ |
| AuAu RHIC (62 GeV) | 0.13 | $4.0 \cdot 10^4$ | $6.1 \cdot 10^1$ |
| p Pb LHC (8.8 TeV) | 100 | $1.0 \cdot 10^7$ | $7.5 \cdot 10^4$ |
| PbPb LHC (5.5 TeV) | 0.5 | $7.3 \cdot 10^6$ | $3.6 \cdot 10^4$ |

Table 2: Nominal yields for J/ψ and Y inclusive production for $y \in [-0.5, 0.5]$ expected per LHC year with AFTER with a 2.76 TeV lead beam on various targets compared to the projected nominal yield (i) in Pb p and PbPb runs of the LHC at 8.8 and 5.5 TeV as well as (ii) in d Au and AuAu collisions at 200 GeV and 62 GeV at RHIC. The integrated luminosity is in unit of nb $^{-1}$ per year, the yields are per LHC/RHIC year.

of quarkonium anomalous suppression, especially given the likely absence of recombination process [14] at this energy. Thanks to the large J/ψ sample, polarisation studies could be carried out providing useful complementary information [107, 108, 109].

8 New observables in quarkonium physics at $\sqrt{s} = 115$ GeV

8.1 Quarkonium single transverse spin asymmetry

Target polarisation (see *e.g.* [110]) is an essential benefit of fixed-target experiments. A transverse polarisation for instance allows for Single Spin Asymmetry (SSA) measurements in production reactions. These SSAs in hard reactions give a handle on a novel class of parton distribution functions, known as Sivers functions [15] (see [17, 18] for recent reviews). These functions express a correlation between the transverse momentum of a parton inside the proton, and the proton-spin vector. As such they contain information on orbital motion of partons in the proton. Nearly nothing is known about gluon Sivers functions which can be probed with quarkonia. These SSA are believed to be due to the rescattering of the quarks and gluons in the hard-scattering reactions, and in general they do not factorise in the standard pattern expected in perturbative QCD.

Recently, measurements from PHENIX [19] have shown that the transverse SSA in $p^\uparrow p \rightarrow J/\psi X$ deviates significantly from zero at $x_F \simeq 0.1$, *i.e.*⁵ $x_p^\uparrow \simeq 0.1$. According to the analysis of [59], this hints at a dominance of a colour-singlet mechanism at low P_T and at a non-zero gluon Sivers effect. Recently, J/ψ and Y SSA studies at AFTER have been investigated [111] with the hypothesis that their production is initiated by $q\bar{q}$ fusion. AFTER at $\sqrt{s} = 115$ GeV with a high luminosity and a good coverage in the rapidity region of the transversally polarised-target (mid and large x_p^\uparrow), may be extremely competitive and complementary to the other existing high-energy particle physics spin projects, in particular as regards gluon Sivers functions. These would be studied via SSA most likely for all the states for which yield measurements are possible and up to so far unexplored x_p^\uparrow .

⁵ x_p^\uparrow is the momentum fraction of the parton emerging from the polarised proton.

8.2 Associated-production channels

8.2.1 Quarkonium-jet/hadron correlation

Quarkonium-jet/hadron azimuthal correlation analysis is a simple measurement which does not require large statistical sample – only an azimuthal distribution is involved – and is not very demanding in experimental requirements. In the nineties, UA1 confronted their distributions of charged tracks against Monte Carlo simulations for a J/ψ coming from a B and a J/ψ coming from a χ_c [112, 113]. The idea was that the activity around the J/ψ would be higher in non-prompt events (because of the remnants of the B decay into J/ψ) than in prompt events, which were thought to come dominantly from χ_c which can be produced without nearby gluons. The same technique has been used by STAR with LO Pythia outputs [34].

At present time, we however expect more complex distributions even for the prompt yield, be it dominated by CO or CS transitions – $J/\psi + 2/3$ gluons process may indeed be significant. It is therefore not clear whether such analyses are suitable to evaluate the B -feed-down. Yet, they are rather easy to implement and may offer interesting complementary results to mere yield measurements. STAR is now working on the analysis of Y data [114]. Such measurements can be carried out at any set-up with a good azimuthal coverage. This should be the case of AFTER.

8.2.2 Double-quarkonium production

Next on the list is double quarkonium production. J/ψ pairs have already been observed at mid and large x_F by NA3 30 years ago [6] ! These results were consistent with double-IC Fock states [115]. The first analysis at the LHC removing the B feed-down has been released by LHCb [116]. Note however that it is at significantly smaller $\langle x_F \rangle \simeq 4 \times 10^{-2}$ despite the forward rapidities accessed by LHCb. Such measurements can be done at AFTER down to large negative x_F . Double- Y production could also be looked for. Kinematical distributions are also worth being investigated. To learn more on these processes, it may be interesting to look at $J/\psi + \psi'$ and $J/\psi + \chi_c$ associated production. NLO theoretical predictions are however lacking for the time being.

8.2.3 Quarkonia plus open heavy flavour

As discussed in section 6.1, the measurement of the rapidity dependence of the cross section of associate production of $J/\psi + D$ is an interesting probe of IC [48]. This process can actually be a significant source of inclusive production of charmonia. Its study is therefore very important both at low and large P_T . For instance $pp \rightarrow J/\psi + c\bar{c}$ is the dominant contribution in the CSM at α_s^4 [70] at large P_T . Prompt $J/\psi + b$ may also be an interesting probe [117] provided that the dominant background from non-prompt $J/\psi + b$ can be efficiently removed. This maybe done by looking at pairs of one prompt J/ψ and one non-prompt J/ψ .

The measurement of the dependence on $J/\psi + D$ invariant-mass yield or on $\Delta\phi$ may also provide important information [48, 118] about the novel phenomena, *e.g.* colour transfers beyond NRQCD factorisation [119]. The measurement of the polarisation of the J/ψ produced with a D meson [120] may also be a discriminant between production models. All these measurements can be efficiently performed at AFTER.

8.2.4 Quarkonium plus isolated photon

The production of the J/ψ and Y in association with a prompt/isolated γ is very likely a useful probe to feed in CO ME global fits since CO fragmentation contributions are sensitive to the $C = +1$ CO transitions, whereas in the inclusive case, it is rather the $C = -1$, $^3S_1^{[8]}$, transition which is involved in $g^* \rightarrow J/\psi X$. Colour singlet contributions are also naturally larger.

In a sense, this process is the continuum background of the resonant $\chi_c \rightarrow J/\psi + \gamma$ signal. However, we are interested in the region where the photon can be easily detected, *i.e.* at large enough P_T and isolated from other charged hadrons. The invariant mass of the $J/\psi - \gamma$ pair is not fixed. The direct cross section and polarisation in the CSM have been evaluated at the LHC energy at NLO [121] and at NNLO* [122] accuracy.

9 Conclusions

We have discussed the numerous contributions that A Fixed Target ExpeRiment on the LHC beams, AFTER, can provide to advance of quarkonium physics. We expect that it can be, in conjunction with the LHC, the key

experiment to help us put an end to quarkonium-production controversies in pp collisions. In pd collisions, quarkonium measurements at AFTER may be the very first to discover that gluon distribution in the neutron is not necessarily equal to that in the proton. In pA collisions, AFTER can produce the largest quarkonium yields ever observed. Its unique access to the far backward region, where novel QCD effects may be at work in nuclear matter, can be a decisive advantage. In PbA, AFTER can expediently complement SPS, RHIC and LHC results in an energy range unexplored so far. This adds to a very good potential for quarkonium excited-state studies in hot and dense nuclear matter. Finally, in polarised pp collisions, precision studies of single transverse spin asymmetries in quarkonium production at AFTER can be essential in the understanding of the gluon Sivers effects, thus of the gluon-motion contribution to the proton spin.

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